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Responses of soil respiration to spring drought and precipitation pulse in a temperate oak forest

Yanchun Liu[a], Cancan Zhao[a], Qing Shang[b], Lei Su[a], Lei Wang[a,*]

[a] State Key Laboratory of Cotton Biology, School of Life Sciences, Henan University, Kaifeng, Henan 475004, China
[b] Yellow River Conservancy Technical Institute, Kaifeng, Henan 475004, China

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ABSTRACT

As a consequence of climate change, a higher frequency of spring drought periods followed by episodic precipitation events is predicted for Central China. Little is known about the effect of drought intensity on the response of soil CO_2 efflux to discrete precipitation events in forest ecosystems. A field experiment was conducted to assess the responses of soil CO_2 efflux to spring drought and precipitation pulse in an oak forest located at climatic transitional zone in Central China. Soil respiration (SR) and heterotrophic respiration (HR) under 30-day drought showed higher responses to precipitation pulse than those under control and 20- day drought treatments. Regardless of drought intensity, precipitation events of 5, 10, and 20 mm levels significantly increased SR by 86.0, 103.4, and 175.2%, and HR by 108.4, 129.5, and 161.5% when compared with non-water addition plots, respectively. Severe drought treatment (30-day drought) amplified the contribution of HR to SR in response to precipitation pulse (84.5% *vs* 78.3% for the control). Drought intensity rather than precipitation amount showed substantial influence on total carbon loss through SR and HR. These findings highlight the importance of incorporating both drought intensity and precipitation events and their impacts on soil carbon cycling into future predictions of forest ecosystems under climate change.

1. Introduction

Recent climate models project that droughts are predicted to increase in duration, intensity, and geographic coverage (Dai, 2011). Concurrently, extreme precipitation events occur frequently across the world (Bytnerowicz et al., 2007; Werner and Egbert, 2009). The increased drying/wetting alterations affect terrestrial carbon (C) cycling, particularly for soil, which comprises the Earth's largest terrestrial C reservoir (Reichstein et al., 2013). Hence, there is an increased interest in quantifying the soil respiration (SR) response to drought and extreme precipitation event (Shen et al., 2016).

Drought is a major natural hazard that is characterized by below-average precipitation over a long period of time (Xu et al., 2015). Droughts occur over most parts of the world, even in humid regions (Dai, 2011). Due to the monsoon climate interacted with the complicated geographical landscapes, many parts of China have suffered from serious droughts in the past 50 years (Xu et al., 2015), which have greatly influenced terrestrial C cycling. Moreover, strong spatial and temporal variations of drought have been reported in China. For example, Wu et al. (2011) quantified drought in China during 1950–2006 and found that Central and Northeastern China had substantial drying trend. In addition, the drought frequency was higher in spring and winter across China (Yu et al., 2014). Understanding the influences of seasonal drought and extreme precipitation events on SR is of primary importance for terrestrial C cycling assessment under scenarios of altered precipitation patterns (Falge et al., 2002; Reth et al., 2005; Xie et al., 2014).

The drying-wetting cycles due to isolated precipitation events can produce pulsed inputs of moisture, resulting in pulse-response CO_2 efflux characteristic that is known as "Birch effect" (Birch, 1964). The pulse magnitude of SR following rewetting of dry soil has been attributed to numerous biotic and abiotic factors, such as pore connectivity (Smith et al., 2017), labile soil organic C (Werner and Egbert, 2009), microbial activity (Blazewicz et al., 2014), accumulated dead microbial biomass over dry periods (Bottner, 1985; Sponseller, 2007), and carbonate dissolution (Rey, 2015). Despite the increasing number of studies and recent advances in our understanding of precipitation pulses, several aspects still need urgent attention. For example, how important is soil microclimate (temperature and moisture) prior to precipitation event in controlling the response of SR to precipitation events remains unclear. Soil respiration rate varies with soil temperature and moisture (Qi and Xu, 2001; Reth et al., 2005; Taylor et al., 2017). Initial soil

* Corresponding author.
E-mail address: wl_mail@henu.edu.cn (L. Wang).

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temperature and moisture directly regulate root activity (Ford et al., 2012), microbial metabolism (Denef et al., 2001), and availability of decomposable organic substrate (Huxman et al., 2004a), thus could have profound impacts on the response of pulse effect. In the Sonoran Desert, for example, the pulse response of SR is intensified by the dry condition of the antecedent soil, but the effect is less obvious if the soil is wet before the precipitation event (Cable et al., 2008). To our knowledge, however, few studies have quantified the effect of antecedent moisture on the response of SR to precipitation events in forest ecosystems.

The Qinling Mountain-Huai River range has been recognized as north-south demarcation zone in China, due to remarkable differences in climate, vegetation, soil, and custom between two sides of the zone. The total area of the demarcation zone is approximately 145,500.74 km^2, with a total length of 1666.28 km from east to west (Zhang et al., 2012), which is also known as a temperate-subtropics transitional zone in China. The forest in this region is characterized by high biodiversity and complex stand structure. Climate zones at middle northern latitudes as well as climatic transitional zones are the ones most sensitive to climate change (Mahlstein et al., 2013). Therefore, it has been suggested that forest ecosystems in climate transitional zone will play progressively important roles in the terrestrial C cycle.

Although a rapid increase of SR following precipitation event has been reported in a variety of ecosystems (Davidson et al., 2000; Sponseller, 2007; Shi et al., 2011; Ma et al., 2012), only a few studies have analyzed the effect of episodic precipitation on different components of SR [autotrophic respiration (AR) and heterotrophic respiration (HR)]. Previous studies suggest that responses of AR and HR to precipitation event differ due to the differences in substrate supply and sensitivity to soil moisture (Huxman et al., 2004b; Sponseller, 2007). For example, in the Sonoran Desert, autotrophic (plant) respiration was a significant (60%) source of respiration and was more sensitive to rainfall pulses (Cable et al., 2008). To date, information on the responses of SR components to precipitation is still rather limited, especially in forest ecosystem. Although water availability is not a limiting factor in most forest ecosystems, discrete rainfall events can also trigger a rapid pulse of soil respiration (Shi et al., 2011). The cumulative triggered pulse of CO_2 from forests is likely contributing more to atmospheric CO_2 concentration due to its greater substrate availability and higher occurrence of precipitation events compared to those in arid and semiarid landscapes (Song et al., 2016).

In this study, short-term responses of SR and HR to spring drought and precipitation events are investigated in an oak forest (*Quercus variabilis* BI.) in Central China. The objectives of the present study are to (1) examine the effects of precipitation events on SR and its components, (2) investigate the effects of different spring drought duration on the responses of SR and its components to precipitation events, and (3) compare the differences of precipitation-induced increase in total soil C loss between different drought intensities.

2. Materials and methods

2.1. Study site

The study site is located at the Jigong Mountains National Nature Reserve (31º46'–31 º50'N, 114 º01'–114 º06'), Henan Province, Central China, within a transitional zone from subtropical climate to warm temperate climate zone. The altitude ranges from 110 m to 810 m *a.s.l.* Long-term mean annual precipitation (1951–2014) is 1063 mm with 66% occurring from May to September. Mean annual temperature is 15.2 °C with monthly mean temperature ranging from 1.9 °C in January to 33.6 °C in July (China Meteorological Data Sharing Service System, http: data.cma.gov.cn). The soil at the site is yellow-brown soil based on China classification (Haplic Luvisol, FAO classification)(Miao et al., 2018).

The vegetation is characterized by warm-temperate deciduous forest. The dominant tree species consist of *Quercus* spp., *Pinus tabuliformis* Carr., *Acer truncatum* Bunge., *P. massoniana* Lamb., and *Cunninghamia lanceolata* (Lamb.) Hook. Woody shrubs include *Lindera glauca* (Sieb. et Zucc.) BI., *Vitex negundo* L., *Symplocos chinensis* (Lour.) Druce, and *Euonymus alatus* (Tunb.) Sieb. Understory herbaceous plants include *Eriophorum comosum* Nees, *Lygodium japonicum* (Tunb.) Sw., and *Corydalis edulis* Maxim. (Chen et al., 2017). The field experiment was conducted in an oak forest (slope < 5°) dominated by *Q. variabilis*, which was approximately 40 years-old. Mean diameter at breast height (DBH) of the stand was 13.4 ± 4.8 cm. Stand density and basal area were 1883.6 tree ha^{-1} and 46.3 m^2 ha^{-1}. Mean soil bulk density and pH are 0.99 ± 0.11 g cm^{-3} and 4.5 ± 0.08 (n = 12), respectively.

Table 1
Number of effective (> 5 mm) precipitation event of different precipitation intensity and average drought duration in the months of spring in the past 20 years (1994–2013) in the study site.

Parameters	Number of precipitation event			
	March	April	May	Average
Precipitation intensity (mm)				
5 < P ≤ 10	0.90	1.31	1.33	1.18
10 < P ≤ 15	0.80	0.57	1.05	0.81
15 < P ≤ 25	0.52	0.76	1.02	0.77
25 < P	0.48	0.70	0.92	0.70
Total	2.70	3.34	4.32	3.45
Average drought duration (day)	11.48	8.97	7.17	9.21

2.2. Experimental design

To assess the effect of spring drought duration on the response of SR to precipitation pulse, a control treatment, representing the average level of soil water availability in this season, is required. According to the meteorological data in the past 20 years (Table 1), we found that the average number of effective (> 5 mm) precipitation event was 3.45 in each month, and the average drought duration was 9.21 days in the spring (Table 1). Therefore, one 10-day rain-free treatment was setup to represent the normal ambient rainfall condition (control). To avoid the impact of episodic rainfall on the control plots during the experimental period, rain shelters were also setup on the control plots for 10 days.

We used a random block design with three blocks as replicates, having 5 m spaces between blocks. Three blocks of 20 m × 20 m area were randomly selected in the oak forest. In each block, twelve 1 m × 2 m plots were laid out in three columns and four rows with a 2 m wide buffer zone between the plots (Fig. 1). Each plot was assigned to one of 12 different treatments: three levels of drought duration [control (10 days), moderate drought (20 days), and severe drought (30 days)] were crossed with four levels of precipitation events (0 mm, 5 mm, 10 mm, and 20 mm) in a factorial design. Placement of the plots was not entirely random as areas with more shrubs distributed were avoided and the plots needed to be accessible for irrigation.

Two 1 m × 1 m subplots were established within each plot. One subplot was randomly selected for the trenching treatment to estimate HR. Trenches of 70 cm deep and 20 cm wide were excavated around each subplot in September 2016. Double nylon net (100 meshes per inches) was lined to prevent roots from penetrating in, and meanwhile get allow lateral transfers of water and solutes (Wei et al., 2015). The trenched subplots were kept free of seedlings and herbaceous vegetation by periodical manual removal throughout the experiment.

Drought treatment was simulated by excluding all the throughfall using rain shelters for different times (10 days for control, 20 days for moderate drought, and 30 days for severe drought). Rain shelters similar to the design of Yahdjian and Sala (2002) were setup on all drought-treatment plots in forest understory on 20 April, after an effective rainfall of 12.4 mm on 19 April 2017. Corrugated polycarbonate

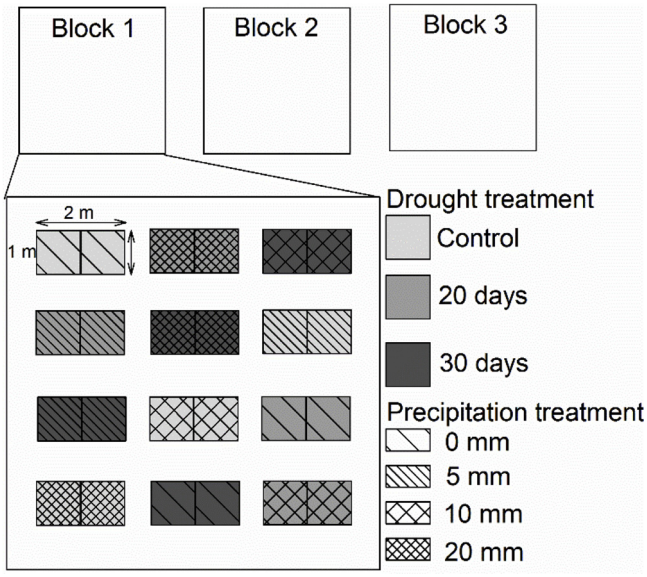

Fig. 1. Experimental design and layout of treatment plots in the field oak forest.

(PC) slats (1.5 m × 2.5 m) covered the roof area of the rain shelter. The PC slats were transparent and able to transmit > 90% of photosynthetically active radiation. The roof was kept approximately 10–15 º slope through setting the two sides at different heights to ensure quick drainage of ambient rainfall. Water collected by the shelters during rain events was transferred into storage tanks and prepared for later precipitation events simulation.

Precipitation events were simulated by spraying a known amount of water evenly within 15–20 min. At the end of each drought treatment (30 April for control, 10 May for moderate drought, and 20 May for severe drought), four plots from each block were randomly selected and assigned four precipitation pulse events (0, 5, 10, and 20 mm). Application of 10 and 20 mm rainfall events resulted in standing water in micro-depressions, but we did not take measurements until this water had infiltrated.

This experiment with drought and precipitation pulse treatments was also conducted in summer, autumn, and winter to determine the seasonal differences in the response of SR to drought and precipitation events (see author's another paper).

2.3. Soil CO_2 efflux, soil temperature, and moisture

A PVC collar (11 cm in internal diameter and 5 cm in height) was permanently inserted 2 cm into the soil in the center of each subplot for CO_2 efflux measurement. It was assumed that the CO_2 efflux investigated in the trenched subplots represented HR while CO_2 efflux measured in the untrenched subplots was SR. Soil CO_2 efflux was determined before each water addition, and then at 5, 15, 35, 65, 125, 305, and 1440 min after precipitation pulse using LI-8100 portable soil CO_2 fluxes system (LI-COR Inc. NE, USA). Soil temperature at the depth of 5 cm was monitored adjacent to each PVC collar using a thermocouple probe (LI-8100-201) attached to the LI-8100 at the same time of soil CO_2 efflux measurement. Volumetric soil moisture of the top 5 cm soil layer was measured at two spots in each subplot adjacent to the PVC collars using a portable soil moisture device Diviner 2000 (Sentek Pty Ltd, Balmain, Australia) at the same time as the soil CO_2 efflux measurements.

2.4. Statistical analysis

The contribution of HR to SR was estimated using the ratio of HR to SR (HR/SR). The total soil C losses (g C m^{-2} day^{-1}) through SR and HR across the 24-hour period was calculated by interpolating soil CO_2 efflux rates between measuring times for each collar. Relative changes (%) of the peak value to the pre-rain value of soil CO_2 efflux were defined as relative peak values of SR and HR induced by precipitation pulse $[(SR_{peak}\text{-}SR_{pre\text{-}precipitation}) \times 100/SR_{pre\text{-}precipitation}]$ (Rey et al., 2017).

Field data were first tested for normality and homogeneity of variance. One-way ANOVA and multiple comparisons (LSD) were used to test the statistical significance of soil temperature and moisture of the plots for SR (ST_{SR}, SM_{SR}) and HR (ST_{HR} and SM_{HR}), SR, HR and HR/SR between drought duration and precipitation events. One-way ANOVA and multiple comparisons (LSD) were also used to test the statistical significance of relative peak values and total C loss between drought intensity and precipitation pulse. Linear regression analysis was used to determine the effects of pre- and post-precipitation soil moisture and temperature on the peak value and total C loss of SR and HR. All analyses were performed using SPSS 16.0 for Windows (SPSS Inc., Chicago, IL).

3. Results

3.1. Soil temperature and moisture

Before precipitation application, both ST_{SR} and ST_{HR} under 20- (17.72 and 17.93 °C) and 30-day drought treatment (22.73 and 22.84 °C) showed greater values than that in the control plots (15.31 and 15.42 °C) ($P < 0.05$, Table 2). In addition, drought intensity showed substantial influences on ST_{SR} and ST_{HR} after precipitation pulse (both $P < 0.05$, Table 3). ST_{SR} in the control plot (15.92–16.68 °C) was significantly lower than that under 30- (22.60–23.64 °C) and 20-day drought treatments (18.03–18.95 °C) (Table 3, Fig. 2a–c). Similarly, ST_{HR} in control plots had substantial lower values than that under 30- and 20-day drought treatments (both $P < 0.05$, Table 3, Fig. 2d–f). However, Precipitation intensity showed no effects on both ST_{SR} and ST_{HR} (all $P > 0.05$, Table 3).

Drought treatment significantly reduced SM_{SR} and SM_{HR} before precipitation addition (both $P < 0.05$, Table 2). The mean values of SM_{SR} and SM_{HR} under 30-day drought (2.78 and 2.99% v/v) was substantially lower than that under 20-day drought (5.22 and 5.65% v/v) and the control treatments (6.03 and 7.12% v/v) ($P < 0.05$, Table 2).

Both SM_{SR} and SM_{HR} showed strong temporal fluctuations after precipitation pulse, which increased right after precipitation additions followed by gradual declines (Fig. 2g–l). Drought intensity significantly influenced post-precipitation SM_{SR} and SM_{HR} ($P < 0.05$, Table 3). SM_{SR} under 30-day drought treatment was on average, 6.07 and 4.68% (absolute value) lower than that under 20-day drought and control treatments, respectively (Table 3). Similarly, SM_{HR} under 30-day drought plot was significantly lower than that in the control plot (Table 3). Regardless of the drought treatment, SM_{SR} under 20 mm

Table 2
Effects of drought intensity on soil temperature (ST) and moisture (SM) of the plots for soil respiration (SR) (ST_{SR} and SM_{SR}) and heterotrophic respiration (HR) (ST_{HR} and SM_{HR}), SR, HR, and proportion of HR in SR (HR/SR) before precipitation pulses ($n = 12$). Values in parentheses are standard errors of means. Different uppercase letters indicate significant differences among different drought intensity ($P < 0.05$).

Drought intensity	ST_{SR}	ST_{HR}	SM_{SR}	SM_{HR}	SR	HR	HR/SR
Control	15.31 (0.11)A	15.42 (0.08)A	6.03 (0.44)C	7.12 (0.49)C	1.65 (0.14)B	1.25 (0.14)B	74.5 (3.1)A
20 days	17.72 (0.36)B	17.93 (0.42)B	5.22 (0.36)B	5.65 (0.28)B	1.43 (0.16)AB	1.23 (0.10)B	76.9 (3.9)AB
30 days	22.73 (0.21)C	22.84 (0.34)C	2.78 (0.18)A	2.99 (0.22)A	1.39 (0.15)A	1.04 (0.07)A	85.7 (4.3)B

Table 3
Effects of drought intensity and precipitation events on the average soil temperature (ST) and moisture (SM) of plots for soil respiration (SR) (ST_{SR} and SM_{SR}) and heterotrophic respiration (HR)(ST_{HR} and SM_{HR}), SR, HR, and proportion of HR in SR (HR/SR) after precipitation pulses (n = 3). Values in parentheses are standard errors of means. Different uppercase and lowercase letters indicate significant differences among different drought intensity and precipitation events (P < 0.05).

Drought intensity	Precipitation events (mm)	ST_{SR}		ST_{HR}		SM_{SR}		SM_{HR}		SR		HR		HR/SR	
Control	0	16.68	A	16.48	A	7.83	B	9.25	B	1.68	A	1.27	A	74.0	A
		(0.20)a		(0.29)a		(0.57)a		(0.78)a		(0.36a		(0.31)a		(2.6)a	
	5	16.10		16.07		10.02		9.94		2.39		1.98		82.9	
		(0.32)a		(0.10)a		(1.00)ab		(0.61)ab		(0.11)a		(0.10)ab		(0.8)b	
	10	15.92		16.15		11.45		13.31		2.67		2.38		89.6	
		(0.56)a		(0.44)a		(0.42)b		(0.54)b		(0.34)a		(0.28)b		(1.0)b	
	20	16.21		16.14		16.70		17.18		4.10		2.77		66.5	
		(0.49)a		(0.29)a		(1.33)c		(2.03)c		(0.50)b		(0.28)b		(4.3)a	
20 days	0	18.95	B	18.92	B	6.06	B	6.41	B	1.67	A	1.27	A	80.6	A
		(0.34)a		(0.55)a		(1.15)a		(0.13)a		(0.60)a		(0.35)a		(5.6)ab	
	5	18.53		17.96		8.52		10.49		2.90		2.54		86.7	
		(0.19)a		(0.38)a		(0.58)ab		(0.41)b		(0.07)b		(0.07)b		(1.2)b	
	10	18.38		18.30		11.61		10.97		2.91		2.58		87.8	
		(0.24)a		(0.41)a		(0.84)b		(1.29)b		(0.23)b		(0.24)b		(1.4)b	
	20	18.03		18.23		14.28		14.48		3.35		2.58		74.9	
		(0.30)a		(0.42)a		(1.37)c		(1.16)c		(0.39)b		(0.29)b		(1.5)a	
30 days	0	23.64	C	23.18	C	2.36	A	2.50	A	1.36	B	1.16	B	86.1	B
		(0.38)a		(0.71)a		(0.08)a		(0.32)a		(0.26)a		(0.19)a		(3.0)b	
	5	22.93		22.74		3.89		5.33		3.47		3.16		90.4	
		(0.37)a		(0.64)a		(0.51)a		(0.28)b		(0.27)b		(0.29)b		(1.3)b	
	10	22.98		22.61		6.55		5.88		4.00		3.50		86.4	
		(0.49)a		(0.33)a		(0.81)b		(0.66)b		(0.17)b		(0.20)bc		(2.2)b	
	20	22.60		22.47		8.92		9.01		5.52		4.28		75.0	
		(0.53)a		(0.49)a		(1.12)b		(0.89)c		(0.37)c		(0.44)c		(5.2)a	

(13.56%) was significantly greater than the other three precipitation levels after precipitation addition (P < 0.05; Table 3, Fig. 2g–i). SM_{SR} under 10-mm precipitation addition (10.06%) was substantially greater than that under 0 mm precipitation (6.05%; Table 3, Fig. 2g–i). Treatments with 20-mm precipitation addition (13.3%) had greater SM_{HR} than the other three precipitation levels (Table 3, Fig. 2j–l). Plots with 10-mm precipitation application (9.87%) showed higher SM_{HR} than those without precipitation application (5.41%; Table 3, Fig. 2j–l).

3.2. Soil respiration

Before precipitation pulse, SR under 30-day drought treatment (1.39 μmol $m^{-2}s^{-1}$) was significantly lower than that in the control plots (1.65 μmol $m^{-2}s^{-1}$) (P < 0.05, Table 2), but no difference was found between 20-day drought plots and control plots (P > 0.05, Table 2). In the control and 20-day drought plots, SR increased rapidly and reached a peak value right after the precipitation pulses (Fig. 3a and b). However, under the 30-day drought treatment, SR reached its peak value 10 min after the 20-mm precipitation addition and then gradually declined (Fig. 3c). After precipitation addition, SR under 30-day drought was 32.5% and 32.3% greater than that under control and 20-day drought plots, respectively (P < 0.05, Table 3, Fig. 3a–c). Regardless of drought intensity, precipitation events with 5, 10, and 20 mm levels significantly increased SR by 86.0, 103.4, and 175.2% compared with 0 mm levels, respectively (Table 3, Fig. 3a–c). In addition, the mean value of SR under 20 mm precipitation (4.32 μmol $m^{-2}s^{-1}$) was substantially higher than that under 5- and 10-mm precipitation events (2.92 and 3.19 μmol $m^{-2}s^{-1}$)(Table 3).

3.3. Heterotrophic respiration

Before precipitation pulse, HR under 30-day drought treatment was substantially lower than that under 20-day drought and the control plots (Table 2). All precipitation treatments resulted in a HR peak right after the precipitation addition in the control and 20-day drought plot, followed by a gradual decline (Fig. 3d and e). However, a lag peak value of HR was found under 20-mm precipitation addition in the 30-day drought plots (Fig. 3f).

After precipitation application, the mean value of HR under 30-day drought treatment (3.02 μmol $m^{-2}s^{-1}$) was significantly higher than that in the control plots (2.09 μmol $m^{-2}s^{-1}$) (P < 0.05, Table 3). However, HR under 20-day drought treatment showed no difference with that in the control plots (P > 0.05, Table 3). Regardless of drought intensity, precipitation events with 5, 10, and 20 mm levels significantly increased HR by 108.4, 129.5, and 161.5% compared with 0-mm levels, respectively (P < 0.05, Table 3). In addition, precipitation event of 20 mm (3.21 μmol $m^{-2}s^{-1}$) showed substantial greater HR than that of 5 mm event (2.56 μmol $m^{-2}s^{-1}$) (P < 0.05, Table 3).

3.4. Proportion of heterotrophic respiration in soil respiration

The contribution of HR in SR (HR/SR) under 20-day drought treatment (85.7%) was significantly greater than that in the control plots before precipitation addition (74.5%) (P < 0.05, Table 2, Fig. 3g–i). After precipitation application, the mean value of HR/SR under 30-day drought (84.5%) was significantly greater than that under control treatment (78.3%) (P < 0.05, Table 3). Regardless of the drought treatment, precipitation events with 5- and 10- mm amount showed significant greater HR/SR (86.7% and 88.0%) than that with 0-mm precipitation events (80.2%) (P < 0.05, Table 3). In the control plots, the values of HR/SR under 5- and 10-mm precipitation events were substantially higher than that under 0 mm precipitation event. However, precipitation addition of 20 mm significantly decreased HR/SR by 11.1% under 30-day drought treatment (P < 0.05, Table 3), but showed no effect in the control and 20-day drought treatment.

3.5. Relative peak value and total C loss

Drought treatment showed no significant effects on the relative peak values of SR and HR (P > 0.05, Fig. 4). The relative peak values of SR and HR positively responded to precipitation size (P < 0.05, Fig. 4), both of which were substantially greater under 20 mm precipitation than that under 5 mm precipitation event (P < 0.05, Fig. 4). However, the relative peak value of SR under 10 mm precipitation showed no difference with that under 5 mm precipitation across all drought treatments (P > 0.05, Fig. 4). Plots with 10 mm precipitation addition

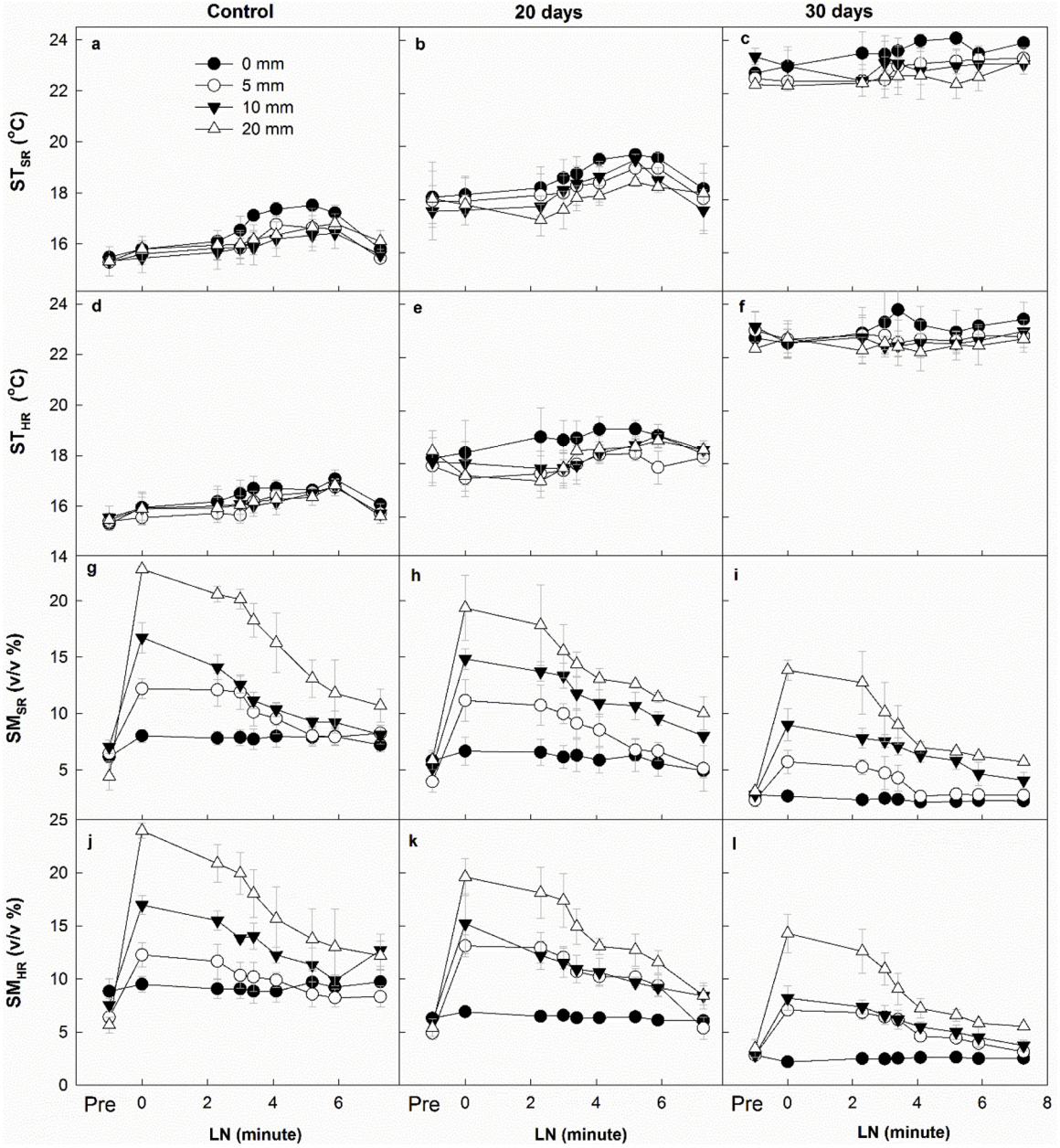

Fig. 2. Time courses of soil temperature (ST) and moisture (SM) of plots for SR (ST_{SR} and SM_{SR}; a, b, c, g, h, and i) and for HR (ST_{HR} and SM_{HR}; d, e, f, j, k, and l) as affected by different precipitation event following different drought intensities (mean ± *S.E.*, $n = 3$). We use a linear scale for the y-axis and a logarithmic scale for the x-axis to make the illustration more readable.

had a greater peak value of HR than that with 5 mm precipitation addition under 30 day drought treatment ($P < 0.05$, Fig. 4), but not under 10- and 20-day drought treatments.

The total soil C loss through SR and HR over the 24-hour period after precipitation addition was significantly affected by drought treatment ($P < 0.05$, Fig. 5a-b). Regardless of precipitation intensity, total C losses of both SR and HR under 30-day drought treatment were significantly greater than the other two drought treatments (Fig. 5a and b). However, no difference was found between 10- and 20- day drought treatments (Fig. 5a and b). In the 30-day drought plots, total C losses of both SR and HR under 5, 10, and 20 mm precipitation events were substantially greater than that under 0 mm precipitation events ($P < 0.05$, Fig. 5a and b). Regardless of the drought treatment, the HR/SR under 20-mm precipitation addition was substantially lower than the other three precipitation levels (0, 5, and 10 mm) ($P < 0.05$, Fig. 5c).

3.6. Dependences of peak value and total C loss of soil CO_2 efflux on soil moisture and temperature

Across three drought and four precipitation treatments, the peak value of SR induced by precipitation pulse increased with post-precipitation soil moisture ($P < 0.01$, Fig. 6b), but showed no correlations with pre-precipitation soil moisture (Fig. 6a). There were no significant correlations between the peak value of SR and pre- and post-precipitation soil temperature (Fig. 6c and d). Our analysis revealed that total C loss by SR showed a negative correlation with pre-precipitation soil moisture ($P < 0.01$, Fig. 6e) but positively relationships with both pre-and post-precipitation soil temperature (both $P < 0.01$, Fig. 6g and h).

The peak value of HR increased linearly with post- but not with pre-precipitation soil moisture (Fig. 7b). Total C loss through HR was strongly negatively related to pre-precipitation soil moisture

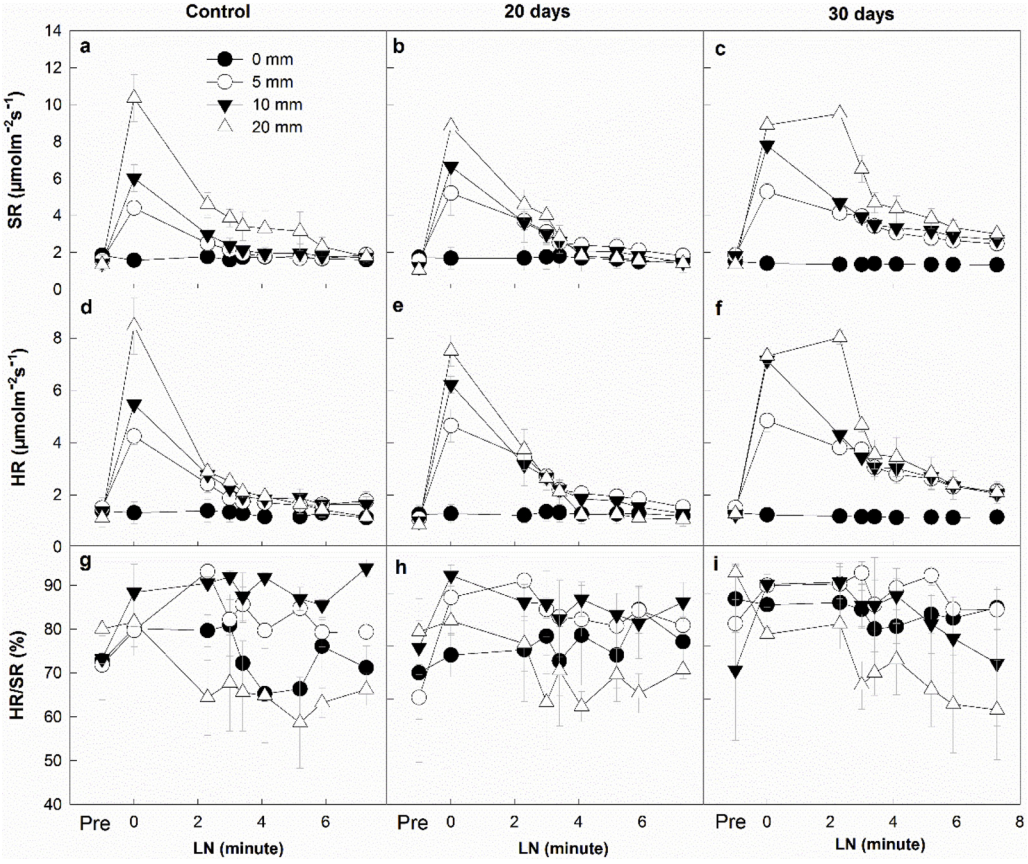

Fig. 3. Time courses of soil respiration (SR; a, b, and c), heterotrophic respiration (HR; d, e, and f), and proportion of HR in SR (HR/SR; g, h, and i) as affected by different levels of precipitation event under different drought durations (mean ± *S.E.*, n = 3). We use a linear scale for the y-axis and a logarithmic scale for the x-axis to make the illustration more readable.

($P < 0.01$, Fig. 7e), however, it was not related to post-precipitation soil moisture (Fig. 7f). Positive correlations between total C loss by HR and pre-and post-precipitation soil temperature were observed in this study (both $P < 0.01$, Fig. 7g and h).

4. Discussion

4.1. Soil respiration increased with the size of precipitation pulse

Our results are consistent with previous studies conducted in a *Pinus canariensis* forest (Brito et al., 2013), an exotic pine plantation (Wang et al., 2012), and a temperate mixed-hardwood forests (Wu and Lee, 2011), where precipitation event leads to rapid increases in SR within minutes. In addition, the finding that peak values of SR following precipitation pulse increased with the precipitation amount, showing the greatest value under 20 mm precipitation event (Fig. 3a–c), is in accordance with studies in semiarid ecosystems (Liu et al., 2002; Huxman et al., 2004b; López-Ballesteros et al., 2016; Rey et al., 2017). This may be partly associated with the intensified aggregate slacking and release of microbial solutes after precipitation application (Lado-Monserrat et al., 2014). In subtropical forest, however, the positive responses of SR to precipitation pulses declined with the increases in precipitation intensity (Deng et al., 2011). These contradictory results may be partly attributed to the use of rainfall amount and the mean annual precipitation of the study site. The excessive soil moisture due to greater amount of applied water (50 and 100 mm) and higher MAP (1965 mm) in Deng's study may reduce soil oxygen concentration and limit soil aeration (van Straaten et al., 2010; Deng et al., 2011).

4.2. Drought enhanced soil respiration response to precipitation pulse

The finding that SR response to precipitation pulse is greater under 30-day drought than that under control and 20-day drought in this study (Table 3) suggests that the response of SR to precipitation events

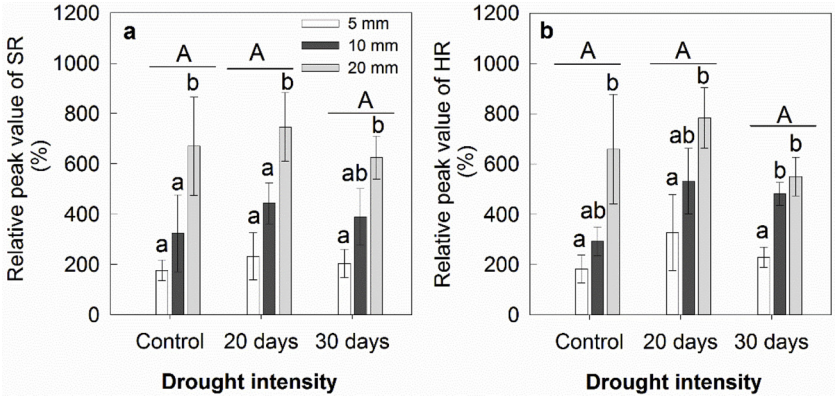

Fig. 4. Relative peak values (relative changes of peak value after precipitation event to the pre-precipitation value of soil CO_2 efflux) of soil respiration (SR, a) and heterotrophic respiration (HR, b) caused by different precipitation events after drought treatments (mean ± *S.E.*, n = 3). Different uppercase and lowercase indicate significant differences between drought intensities and precipitation events ($P < 0.05$).

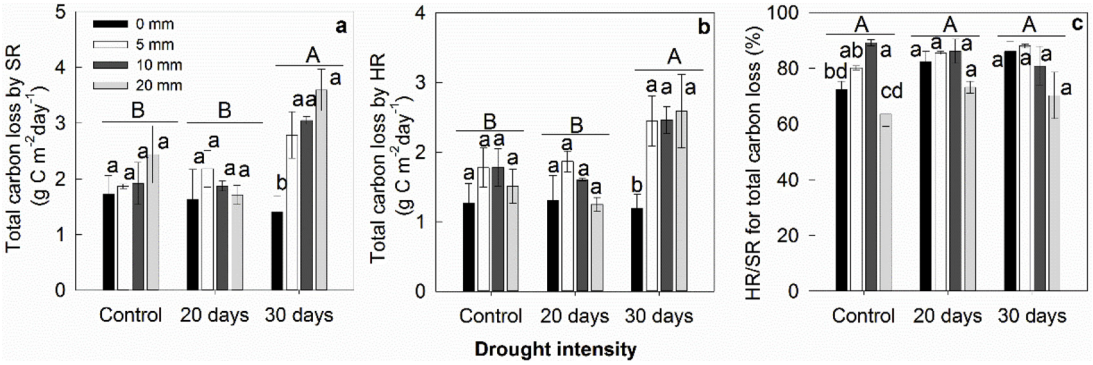

Fig. 5. Total carbon loss through soil respiration (SR, a) and heterotrophic respiration (HR, b), and proportion of HR in SR for total carbon loss (HR/SR, c) induced by precipitation events following different drought treatments. Different uppercase and lowercase indicate significant differences between drought intensities and precipitation events, respectively (mean ± *S.E.*, n = 3).

in oak forest depends on the preceding soil water condition. This was consistent with the results in the Sonoran Desert (Cable et al., 2008) and a subtropical forest ecosystem (Deng et al., 2011), where the increased CO_2 efflux induced by precipitation pulse was inversely related to the pre-rain soil moisture. Therefore, similar to semiarid ecosystems (Sponseller, 2007; Cable et al., 2008), a precipitation pulse has the highest effect on soil CO_2 efflux in this forest ecosystem when it is large and occurs during a long dry period. One possible explanation for this response was that physical displacement of CO_2 from soil pore spaces following water infiltration into dry soil might contribute to a higher CO_2 efflux following drier conditions (Liu et al., 2002). Moreover, compared with the wet condition, pre-precipitation dry conditions can increase the responsiveness of microbial turnover and root activity to precipitation pulse (Fierer and Schimel, 2003; Cable et al., 2008; Deng et al., 2011). Therefore, the same precipitation pulses in the dry season should result in greater stimulation of microbial and root respiration, then larger soil CO_2 efflux.

4.3. Drought enhanced HR/SR response to precipitation pulse

In this study, the substantial greater response of HR/SR to precipitation pulse was found under 30-day drought compared with the control plots (Table 3 and Fig. 3g–i), which was consistent with the results reported in Sonoran Desert (Cable et al., 2008). Based on the measurement of SR from the bare and vegetated soils, Cable et al. (2008) observed that wet antecedent conditions decreased the effect of precipitation pulse on HR, while dry antecedent conditions had the opposite effect (Cable et al., 2008). Likewise, elevated HR has been found during the dry season in a black locust stand, and contributed more to SR in response to precipitation pulse (Shi et al., 2011). The positive effect of drought on the response of HR/SR to precipitation pulse may result from the substrate accumulation during drought period. Pulses of CO_2 efflux seems to be fueled by a resource pool that increases in size with time between rainfall events (Sponseller, 2007). This interpretation can be supported by the studies suggesting that ammonium (Welter et al., 2005) and labile dissolved organic C (Ritson et al., 2017) increase in soils during prolonged dry periods. The accumulated soil resource may attribute to microbial growth and nutrient mineralization (Meisner et al., 2015; Gao et al., 2016) between precipitation events, and the photochemical degradation of litter and soil organic matter (Austin et al., 2016). Moreover, microbial cell lysis and release of intracellular solutes also contribute to the increase of resource pool (Kieft et al., 1987).

The results of this experiment show that responses of HR/SR to

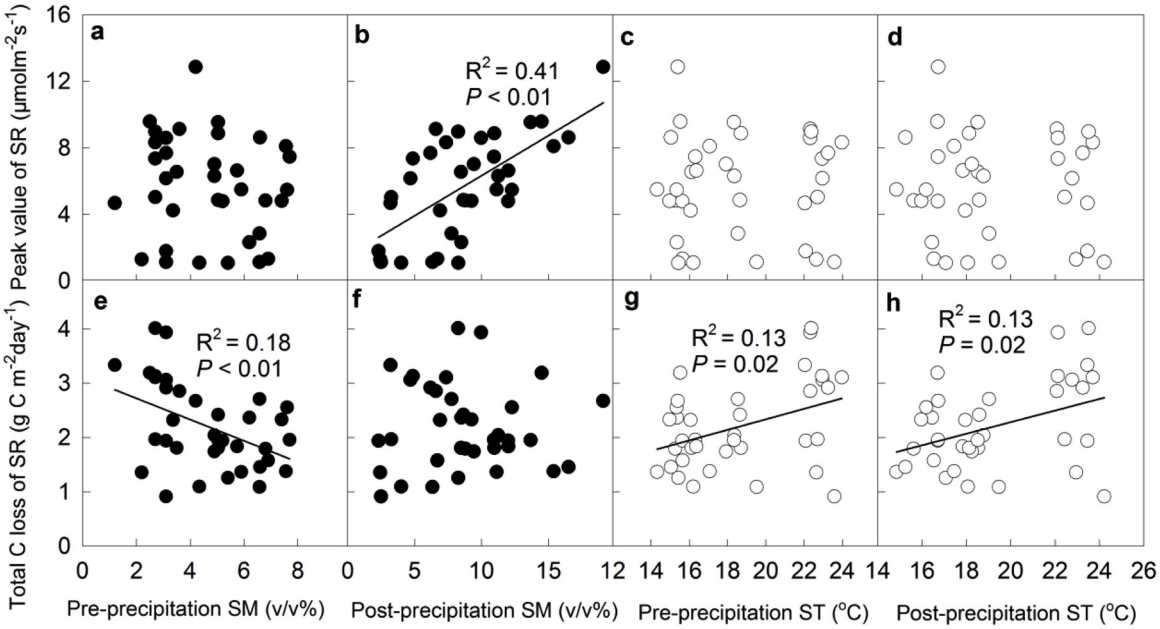

Fig. 6. Effects of pre- and post-precipitation soil moisture (SM; a, b, e, f) and temperature (ST; c, d, g, h) on the peak values and total carbon loss of soil respiration (SR) across all treatments.

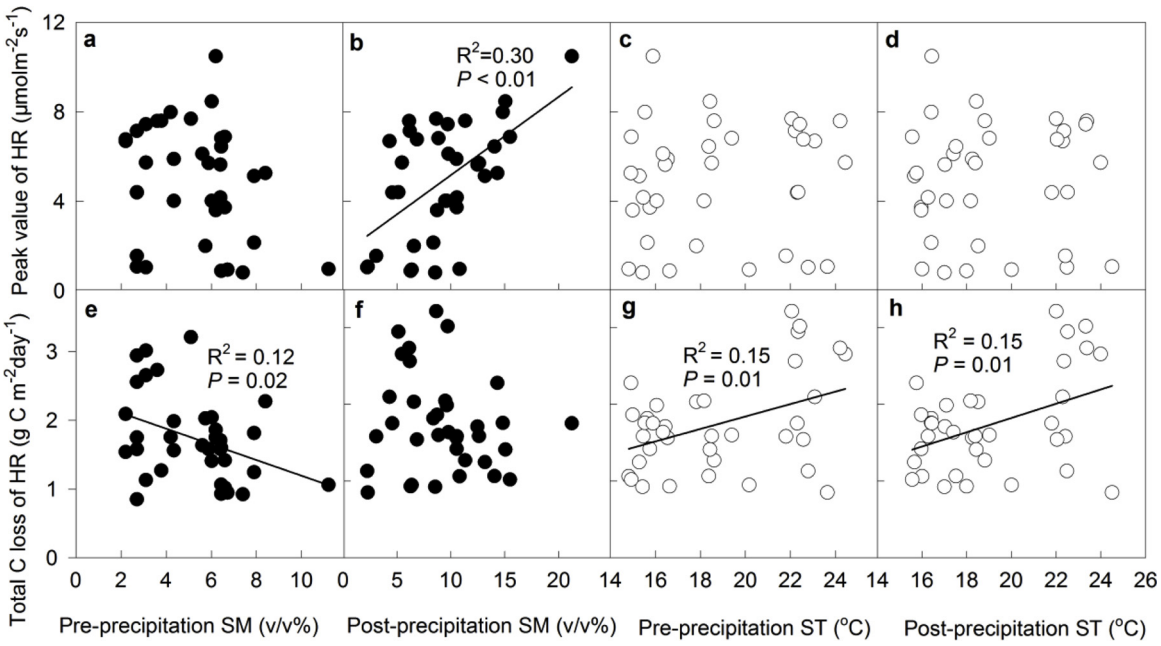

Fig. 7. Effects of pre- and post-precipitation soil moisture (SM; a, b, e, f) and temperature (ST; c, d, g, h) on the peak values and total carbon loss of heterotrophic respiration (HR) across all treatments.

precipitation varied with precipitation amount, with a positive response under 5- and 10-mm rainfall, but a negative response under 20 mm rainfall event (Table 3 and Fig. 3g–i). These results may be attributed to the changes in environmental factors induced by different precipitation intensities. On one hand, greater labile organic C and soil microbes are concentrated within the top surface layers, indicating that higher precipitation event (20 mm in this study) penetrating to greater depth do not lead to significantly releases of HR compared with rainfall that only wet the soil surface (Sponseller, 2007). On the other hand, larger precipitation pulses can shift available water to deeper soil layers where plant roots are primarily located (Liu et al., 2014), thus may elevate the contribution of autotrophic respiration to soil C loss (Cable et al., 2008).

4.4. Response of total C loss and peak values to drought and precipitation events

Despite the transient nature of these pulses, soil C losses caused by rainfall events can be important at the ecosystem level. We found that rainfall events of < 20 mm represent more than 80% of spring rainfall events in our study region. The total C losses caused by precipitation pulses would reach up to 52.5 g m^{-2}, which is a considerable amount of C emission (48.6%) in spring. This suggests that light but frequent rainfall event in spring may represent a substantial C loss for these forest ecosystems.

In our study, drought intensity rather than precipitation event showed a substantial impact on soil total C loss (Fig. 5). Since the magnitude of the total C loss differed significantly among drought intensities, this study highlights the importance of antecedent soil water content regulated by drought period. As expected, SR under severe drought was more responsive to increased rainfall size than mild and moderate drought treatments (Fig. 5). Similar to our findings, some studies have observed that the same precipitation event had greater influences on soil total C loss under drier antecedent soil moisture (Cable et al., 2008; Wu and Lee, 2011; Yan et al., 2014). There are several potential explanations for the positive effects of severe drought on total C loss. First, longer drought period could lead to greater substrate accumulation due to weakened microbial activity and increased microbial cell lysis (Yan et al., 2014). Second, soil water deficiency under severe drought could increase belowground C allocation and promote root growth, thus stimulate root respiration (Liu et al., 2014, 2016).

Contrary to the response patterns of total C loss, however, the relative peak values of SR and HR were substantially affected by precipitation intensity, but not by drought intensity (Fig. 4). The differential response patterns of peak value and total C loss to drought and precipitation treatments was likely attributed to the variations in the source of soil CO_2 efflux induced by treatments. Once water is applied to dry soils, it could trigger a few mechanisms influencing soil CO_2 efflux with different response times. Additional water can fill soil pores and displace CO_2 highly concentrated air, leading to degassing (Smith et al., 2017). Degassing is the fastest response, usually happens within minutes after water applications, which could be considered as the main source of peak value of SR and HR. As it has been suggested and discussed above, water application to dry soils activates microbe and root activity (Cable et al., 2008; Wu and Lee, 2011), also resulting in an increase of soil CO_2 efflux. Different from the physical displacement of CO_2, however, the enhanced microbial turnover and root growth might take several hours to days. Therefore, the soil CO_2 efflux induced by microbe and plant activity may play an important contribution to the total C losses across a period following rewetting.

4.5. Effects of site condition on the response of soil CO_2 efflux to drought

In this study, both SR and HR were significantly decreased under severe drought treatment (30-day); supporting most of previous studies (Selsted et al., 2012; Schindlbacher et al., 2012; Deng et al., 2017). Inconsistent with this observation, however, increased SR under drought treatment has been reported in another oak forest (Liu et al., 2016). These contradictory findings could be attributed to the differences in soil texture and microbial activity between the two ecosystems. In terms of soil texture, the soil in this study belongs to sand soil, mixed with many large and small stones. Therefore, it may have a lower water holding capacity than our previous experiment conducted in loamy soil forest (Liu et al., 2016). Compared with loamy soil forest, sporadic drought events may lead to severe water stress in sand soil forests, thus decrease soil microorganism activity and metabolism. Heterotrophic respiration is the main component of soil CO_2 efflux in this study,

accounting for 68–87% (Table 2), which is higher than our previous study in loamy soil forest (50.5–70.6%) (Liu et al., 2016). Therefore, another plausible explanation for the difference in the response of soil CO_2 efflux to drought treatment could be elevated root respiration under drought treatment in the loamy soil forest. Drought treatment increased fine root growth and turnover in our previous study in the loamy soil forest (Liu et al., 2016). Spring drought, which has been proved to be more frequent in China (Yu et al., 2014), affects not only the current soil CO_2 efflux, but also the later rate of CO_2 efflux due to its lagging effects on plant and soil microbial activity. Therefore, we analyzed the short-term responses of soil respiration to drought and precipitation pulse in spring. Considering the intra-annual variation in plant and soil characteristic, we explore the seasonal differences in the responses of soil respiration to precipitation pulse in another paper.

5. Conclusions

In an oak forest located at climatic transitional zone in Central China, spring drought intensity and precipitation events play an important role in soil CO_2 emission. The results from this study suggest that drought intensity enhanced the response of SR and HR to precipitation pulse. Soil respiration following precipitation events increased with the precipitation amount regardless of drought duration. In addition, HR is the dominant component responsible for the changes in SR under severe drought conditions. Total C loss after precipitation pulse depends on antecedent soil water condition that regulated by drought duration. Post-precipitation soil moisture showed positive influence on the peak value of SR and HR, but not affect total C loss. From the viewpoint of climate change and forest C cycling, soil C losses as a result of seasonal drought and episodic precipitation events need to be taken into account in assessments of the terrestrial C balance.

Acknowledgments

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